

TRANSVERSE SPIN AND RHIC

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The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is the first accelerator facility that can accelerate, store and collide spin polarized proton beams. This development enables a physics program aimed at understanding how the spin of the proton results from its quark and gluon substructures. Spin states that are either parallel (longitudinal) or perpendicular (transverse) to the proton momentum reveal important insight into the structure of the proton. This talk outlines future plans for further studies of transverse spin physics at RHIC.

1. Introduction

There has been renewed experimental and theoretical interest in transverse spin physics. Large transverse single-spin asymmetries (SSA) observed in elastic proton scattering and particle production experiments (hyperon production and pion production) were often viewed as a challenge to QCD, since the chiral properties of the theory should make transverse single spin asymmetries small for inclusive particle production. Many people believed that transverse SSA would disappear when studying polarized p+p collisions at higher collision energies (\sqrt{s}) now possible at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory.

The modern perspective views transverse SSA as a challenge to our understanding of hadrons on long distance scales, possibly providing sensitivity to the transversity structure function or to spin- and transverse-momentum dependent distribution functions that are related to parton orbital motion.

In this contribution, I briefly review transverse SSA and related measurements completed at RHIC to date and describe what new measurements are expected in the near-term future.

2. Recent developments in transverse spin physics

This workshop surveyed ongoing experimental and theoretical work. A deeper understanding of spin- and transverse-momentum dependent distribution functions (embodied in the Sivers effect¹) and fragmentation functions (one of the keys to the Collins effect²) has recently emerged. The former were known to violate “naive” time reversal symmetry. Results from a specific model demonstrate their possible existence³. This important theoretical development was essentially concurrent with experimental results from semi-inclusive deep inelastic scattering from a transversely polarized proton target that unambiguously observed a non-zero Sivers effect⁴. Also concurrent was the observation of large spin effects in dihadron correlations from e^+e^- collisions that indicates that spin-dependent fragmentation effects are large. This is one of the keys to the Collins effect⁵. These experimental developments, coupled with the observation of non-zero single spin asymmetries in inclusive pion production from the first collisions at RHIC, have led to a reinvigoration of transverse spin physics.

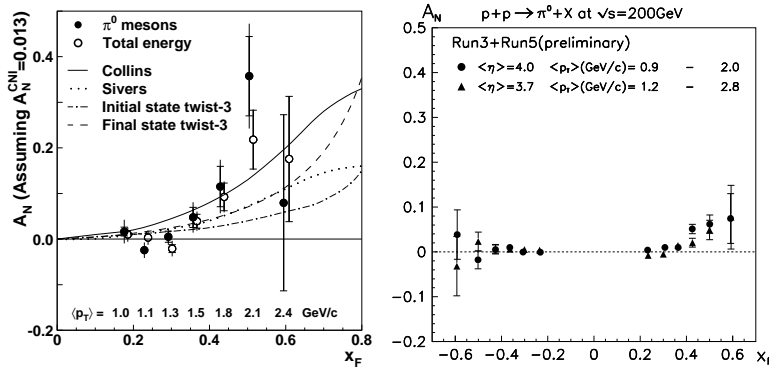


Figure 1. (left) First results for $p_{\uparrow} + p \rightarrow \pi^0 + X$ analyzing powers (A_N) at $\sqrt{s} = 200$ GeV compared to theoretical predictions available prior to the measurements. (right) More precise preliminary results, using on-line measurements of the beam polarization, for π^0 production A_N obtained in subsequent runs.

Large SSA were observed for $p_{\uparrow} + p \rightarrow \pi^0 + X$ at $\sqrt{s} = 200$ GeV by the STAR collaboration⁶ in the first polarized proton collisions at RHIC. They confirmed the expectation^{7,8,9,10}, not shared by all, that the sizeable SSA observed for pion production at $\sqrt{s} = 20$ GeV¹¹ would persist at an order of magnitude higher collision energy. These expectations are shown by the theoretical predictions in Fig. 1, available prior to the measure-

ments. Subsequent development of full integration over intrinsic transverse momentum has modified the relative contributions to transverse SSA from different sources¹². More recent data¹³ have improved the statistical precision of the effect and given the first hint of its separated x_F and p_T dependence. Preliminary results from the BRAHMS collaboration indicate that mirror asymmetries ($A_N(\pi^-) \approx -A_N(\pi^+)$) are observed for large rapidity π^\pm production¹⁴, similar to the lower-energy results¹¹.

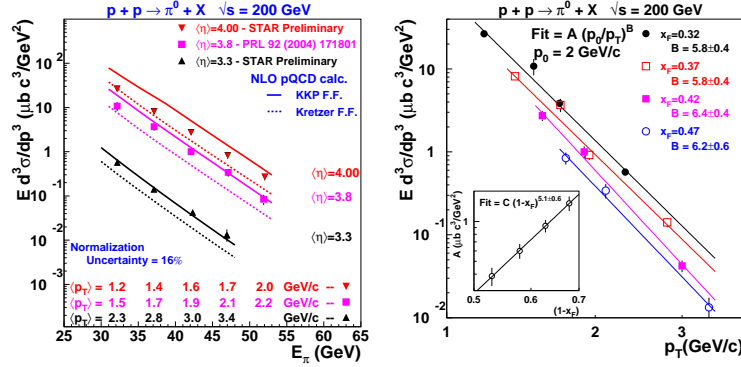


Figure 2. Results for $p + p \rightarrow \pi^0 + X$ cross sections at $\sqrt{s} = 200$ GeV compared to NLO pQCD calculations using conventional parton distribution and fragmentation functions. (right) Parameterized x_F and p_T dependence.

Perhaps most significantly, it has been established that π production cross sections at RHIC collision energies, in the kinematics where single spin effects are observed, are consistent with next-to-leading order perturbative QCD (NLO pQCD) calculations at $\sqrt{s} = 200$ GeV (Fig. 2). This is in marked contrast to the situation at lower \sqrt{s} where measured cross sections far exceed NLO pQCD predictions¹⁵, apparently consistent with the belief that the transverse SSA in hadroproduction were due to beam fragmentation. The NLO pQCD description at $\sqrt{s} = 200$ GeV describes particle production being due to partons from both beams undergoing a hard scattering prior to fragmenting to the observed hadrons. That description is further supported by experimental data that shows a significant back-to-back peak for hadrons detected at midrapidity for events where a large rapidity π^0 is observed¹⁶.

Measurements of the cross section for inclusive π^0 ,¹⁷ charged hadron¹⁸ and jet production¹⁹ at midrapidity have been completed and compared with NLO pQCD calculations²⁰. Quantitative agreement with calculations

has been found. This agreement is an important basis for the interpretation of spin observables (A_N and the helicity asymmetry, A_{LL} , that is sensitive to gluon polarization). Transverse SSA for midrapidity π^0 and charged hadron production¹⁸ have been measured and are consistent with zero with a precision comparable to the non-zero A_N found at large rapidity at the same p_T of ~ 2 GeV/c. The midrapidity results may lead to important constraints on the magnitude of the gluon Sivers function.

3. The future

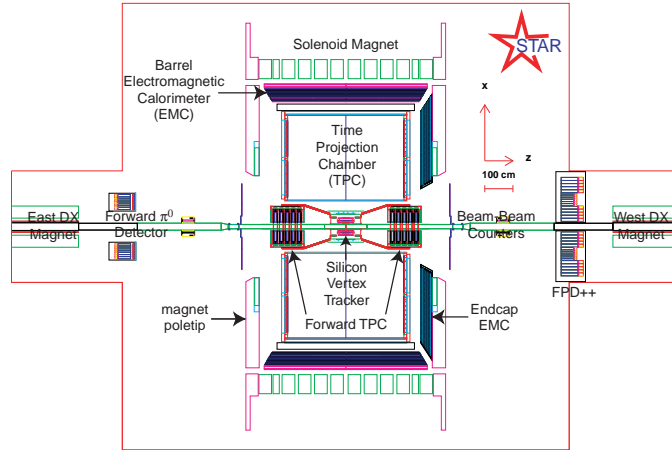


Figure 3. Layout of the STAR experiment for RHIC run 6. The Forward π^0 Detector (FPD) arrays shown east of the STAR magnet were also present in earlier runs west of the STAR magnet. For run 6, the west FPD has been upgraded to become the FPD++. The Forward Time Projection Chamber provides information about charged hadrons in the angular range spanned by the forward calorimetry.

I'll restrict attention to the near-term future since there will be significant data sets obtained with transverse polarization during the upcoming RHIC run following the resolution of budgetary problems. A main objective for midrapidity studies of $p_T + p$ collisions at $\sqrt{s}=200$ GeV is to establish if there are spin effects correlated with k_T , a transverse momentum imbalance that is observable if more than one particle, or more than one jet, is observed. Such effects could be a signal of a non-zero Sivers function for gluons²¹. STAR (Fig. 3) plans to measure k_T for di-jet events (Fig. 4) and will use vertical polarization. The projected sensitivity is based on existing

unpolarized data for the azimuthal angle difference between pairs of midrapidity jets²³. PHENIX plans to measure k_T by detecting pairs of hadrons in their central arms whose symmetry requires radial polarization to observe a spin effect. Non-zero transverse SSA for midrapidity dihadron production may have contributions from both the Sivers effect and the Collins effect²².

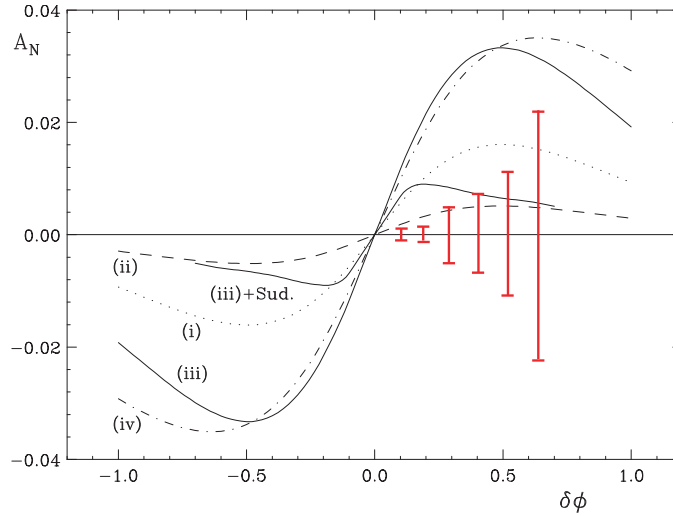


Figure 4. Projected sensitivity to the analyzing power versus the azimuthal angle difference between pairs of jets detected at midrapidity for a data sample corresponding to 5 pb^{-1} with beam polarization of 50% compared to theoretical expectations from different models of the gluon Sivers function as discussed in the text.

A portion of the upcoming RHIC run will be devoted to collisions of transversely polarized protons at $\sqrt{s}=62 \text{ GeV}$. BRAHMS aims to measure transverse SSA for inclusive production of identified charged hadrons at large rapidity ($\eta \approx 3.3$ and 3.9) from these collisions. Their particle identification apparatus will permit measurements up to $x_F \approx 0.6$ at the lower \sqrt{s} . The unpolarized cross section systematics discussed earlier¹⁵ would greatly benefit from new forward angle results at $\sqrt{s}=62 \text{ GeV}$. In the remainder of this section, I'll discuss plans in the upcoming RHIC run for measurements with increased acceptance forward calorimetry in STAR.

An important goal is to address the relative contributions from the Collins and Sivers effects to the transverse SSA observed for inclusive forward pion production. One way to disentangle the contributions is to address the question “*is there a significant transverse single spin asymmetry*”

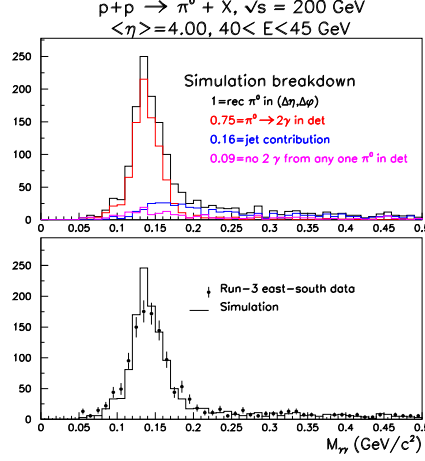


Figure 5. (bottom) Di-photon invariant mass distribution for events with at least two reconstructed photons. Data compares well to PYTHIA/GEANT simulations. (top) Contributions to simulated di-photon invariant mass distribution for $N_\gamma > 1$ events. Jet-like events are evident.

for jet-like events in $p+p$ collisions?

Jet-like events are defined as having three or more photons which are mostly a π^0 and accompanying particles or single photon daughters from two or more π^0 . In either case, multiple fragments of the parton scattered through small angles are observed, making the events manifestly jet like. If the detector acceptance for the observed particles is azimuthally symmetric around the thrust axis of the forward scattered parton, then a transverse SSA for jet-like events must be due to the Sivers effect¹. Integration over all particles detected in an acceptance that is azimuthally symmetric around the thrust axis ensures cancellation of possible contributions from spin- and k_T -dependent fragmentation functions that serve to analyze quark polarizations transferred to the final state (Collins effect²). Particularly for events at large x_F , the forward π^0 carries a large fraction of the energy of the forward scattered parton. A precise definition of jet-like behavior is required.

We know that jet-like events are present at large η from results with the STAR Forward Pion Detector (FPD). Fig. 5 shows the reconstructed invariant mass distribution, where $M_{\gamma\gamma} = E_{trig} \sqrt{1 - z_{\gamma\gamma}^2 \sin^2(\phi_{\gamma\gamma}/2)}$. The total energy (E_{trig}) corresponds to the sum of energy from all towers of

one of the FPD modules and is taken as the π^0 energy in the analysis. It is used in conjunction with the opening angle ($\phi_{\gamma\gamma}$) and energy sharing, $z_{\gamma\gamma} = |(E_{\gamma 1} - E_{\gamma 2}) / (E_{\gamma 1} + E_{\gamma 2})|$, from the two highest energy photons reconstructed in the event. Jet-like events occur when more than two photons are found, resulting in $E_{trig} > E_{\pi}$ and therefore $M_{\gamma\gamma} > M_{\pi}$. This is observed in Fig. 5 and is accounted for by simulation, which is decomposed into its various contributions. But, events in the FPD at a given x_F occur primarily in portions of the calorimeter closest to the beam because this minimizes p_T (see right panel of Fig. 2). For such events the FPD does not have azimuthally symmetric acceptance around the thrust axis for additional particles distributed around the reconstructed π^0 .

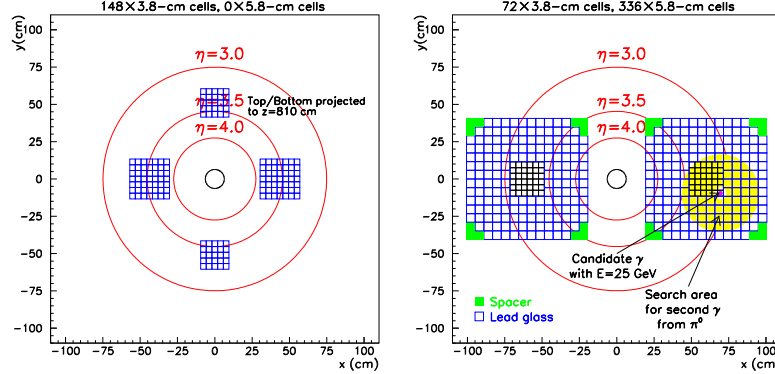


Figure 6. (left) Layout of STAR forward pion detector used in run 5. (right) Layout of STAR FPD++ that is planned for use in run 6.

The issue of azimuthally symmetric coverage for jet-like events is resolved by an upgrade known as the FPD++ (Fig. 6) that has been built for the upcoming RHIC run as an engineering test of the STAR Forward Meson Spectrometer (FMS)²⁵. It consists of two left/right symmetric calorimeters that replace the FPD modules west of the STAR interaction point. The original FPD modules remain on the east side of STAR and are planned to improve the precision of transverse SSA measurements at large x_F . As shown in Fig. 6, the inner portion of each calorimeter module is essentially identical to the FPD. The outer portion of the calorimeter consists of larger cells²⁶ that are placed with azimuthal symmetry about the inner portion. Events can be selected with the FPD++ in an identical manner as used for the FPD that result in sizeable transverse SSA for π^0 production. The ad-

ditional detector coverage can be queried for evidence of additional photons that accompany a trigger π^0 thereby signaling jet-like events. Based on the diphoton invariant mass distribution and the photon multiplicity distribution, at least 16% of the π^0 events observed in the FPD with $E_\pi \geq 20$ GeV are accompanied by additional photons in jet-like events.

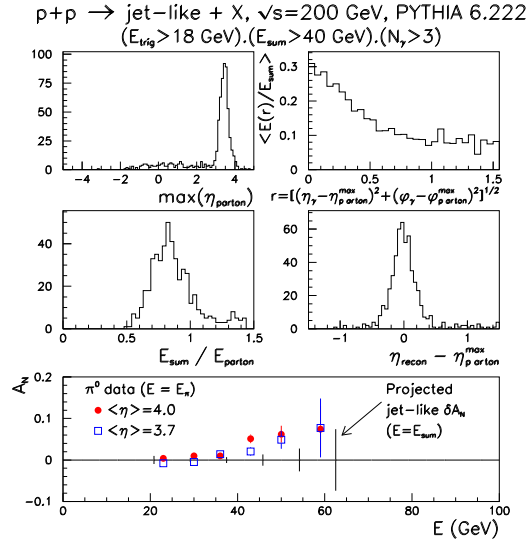


Figure 7. PYTHIA simulations of FPD++ response for p+p collisions at $\sqrt{s}=200$ GeV. E_{trig} (E_{sum}) is the energy sum in the central section (entire) of the calorimeter (Fig. 6. (upper left) most forward hard-scattered parton pseudorapidity distribution; (upper right) distribution of photon energy relative to the thrust axis showing a standard jet shape atop an underlying event contribution; (middle left) photon energy sum scaled by the most forward hard-scattered parton energy; (middle right) difference distribution of the η reconstructed from the vector sum of the detected photon momenta and the parton η ; (bottom) projected statistical precision for jet-like events for 5 / pb of polarized proton integrated luminosity.

Fig. 7 shows PYTHIA 6.222²⁷ simulations that provide an operational definition of what we mean by jet-like events. PYTHIA is expected to have predictive power in this kinematics because it has been previously shown to agree with measured forward pion cross sections²⁸. To explore jet-like events, minimum-bias PYTHIA events are selected when the summed photon energy in the inner portion of a FPD++ module, defined as E_{trig} , exceeds 18 GeV. To facilitate possible reconstruction of forward $\pi^0 + \pi^0$ pairs, events are further required to have more than 3 photons within the

full acceptance of an FPD++ module. These requirements mean that selected events with energy from incident photons summed over the entire FPD++ module (E_{sum}) may exhibit jet-like behavior. The upper left panel of Fig. 7 shows the pseudorapidity distribution of the most forward angle hard-scattered parton when $E_{sum} > 40$ GeV. It is peaked at $\eta \approx 3.3$, corresponding to the location of the triggering portion of the FPD++ module. The small background near midrapidity has contributions from large Bjorken x quarks that emit initial-state radiation that subsequently scatters from soft gluons from the other proton. The distribution of the photon energy relative to the thrust axis of the forward scattered parton is shown in the upper right panel of Fig. 7. Jet-like behavior is evident, although evidence for contributions from the underlying event is also present. The summed photon energy within the FPD++ acceptance gives a good representation of the forward scattered parton, albeit shifted in its energy scale. Furthermore, the vector sum of the detected photon momenta faithfully reconstructs (η_{recon}) the direction of the scattered parton. From the middle right panel of Fig. 7, the symmetry of the $\delta\eta = \eta_{recon} - \eta_{parton}^{max}$ distribution indicates that the underlying event is not skewed from fragments of the beam jets. Projections for the uncertainties that could be measured on the A_N for these jet-like events with 5 pb^{-1} of integrated luminosity recorded in a data sample with beam polarization of 50% are shown in the bottom panel of Fig. 7.

In addition, the FPD++ is expected to allow for robust detection of large x_F direct photon production. Rather than searching for coincident photons, the outer portion of the calorimeters can serve to remove neutral meson contributions, to extract events with only a single energetic photon observed in the calorimeter. The resulting yield would be predominantly prompt photon events, including direct photons and fragmentation photons. The calorimetric coverage will allow suppression of most of the latter events. We expect $\approx 70,000$ direct photon events with $E \geq 25$ GeV in a data sample from the FPD++ that records 5 pb^{-1} of $p + p$ collisions at $\sqrt{s}=200$ GeV. These photon energies are larger than the simulated cutoff in the distribution of energy deposition by charged hadrons incident on the calorimeter.

The left/right symmetry of the FPD++ is important for the cancellation of systematic errors. With that symmetry, so-called cross ratio methods can be used for extracting single-spin asymmetries for π^0 production, jet-like events and prompt photon events. Another benefit of the symmetry is for coincident events. The opening angle between the two calorimeters is well

matched to that required for large- x_F production of objects with invariant mass of order 3 GeV/ c^2 that decay to either photons, neutral mesons or electron-positron pairs.

The end result is that the upcoming RHIC run should provide exciting results for transverse spin physics. Perhaps of greatest interest is the prospect for isolation of the Sivers function both at midrapidity and for forward particle production. Its isolation may establish the dynamical origin of transverse SSA for large- x_F π production and may conclusively demonstrate orbital motion of the constituents of the proton.

4. Acknowledgements

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